Magnet System for an ECR Ion Source

C.Taylor, S. Caspi, J.Y. Chen, M. Leitner, S. Lundgren, C. Lyneis, S. T. Wang*, D. Wuttle,
Lawrence Berkeley National Laboratory, Wang NMR, Inc.*

A superconducting magnet assembly has been built for an ECR Ion source at the 88-inch cyclotron at LBL. Three 32 cm ID solenoids provide axial plasma confinement and a sextupole assembly in the solenoid bore provides radial stability. Two large solenoids are spaced 50 cm apart with a smaller opposing solenoid in between. The sextupole assembly is 92 cm long with winding inner diameter of 20 cm and outer diameter of 27.2 cm. The design goal is to achieve a field on axis of 4 T and 3 T at the mirrors with 0.4 T between and a radial sextupole field of 1.9 T at a 14.4 cm diameter.

Each solenoid uses rectangular conductor with copper/SC ratio of 4; the three coils are wet-wound on a one-piece aluminum bobbin with aluminum banding for radial support. The sextupole uses rectangular conductor with copper/SC ratio of 3. Each of the 6 coils is wet-wound with filled epoxy on a ten-degree pole; the ends of the pole are aluminum and the central 34 cm is iron to augment the sextupole field. The six coils are assembled on a 20 cm OD stainless steel tube with a 1.4 cm thick 30 cm OD aluminum tube over the assembly for structural support. Thin metal bladders are expanded between each coil to pre-load the assembly. The sextupole assembly fits inside the solenoid bobbin, which provides support for the magnetic forces. Test results and design features are presented for this design and an earlier R and D version.

Magnet System for an ECR Ion Source

C.Taylor, S. Caspi, M. Leitner, S. Lundgren, C. Lyneis, D. Wutte; Lawrence Berkeley National Laboratory

S. T. Wang, J.Y. Chen; Wang NMR Inc., Livermore, CA

Abstract - A superconducting magnet assembly has been built for an ECR (Electron Cyclotron Resonance) Ion source at the 88-inch cyclotron at LBL[1]. Three 34-cm ID solenoids provide axial plasma confinement and a sextupole assembly in the solenoid bore provides radial stability. Two large solenoids are spaced 50 cm. apart with a smaller opposing solenoid between. The sextupole assembly is 92 cm long with winding inner diameter of 20 cm. and outer diameter of 27.2 cm. The design goal is to achieve a field on axis of 4 T and 3 T at the mirrors with 0.4 T between and a sextupole field of 2.0 T at 15-cm diameter in the confinement volume.

Each solenoid uses rectangular conductor with copper/SC ratio of 4; the three coils are wet-wound on a one-piece aluminum bobbin with aluminum banding for radial support. The sextupole uses rectangular conductor with copper/SC ratio of 3. Each of the 6 coils is wet-wound with filled epoxy on a metal pole; the ends of the pole are aluminum and the central 34-cm is iron to augment the sextupole field. The six coils are assembled on a 20-cm-OD stainless steel tube with a 1.4-cm thick 30.0-cm OD aluminum tube over the assembly for structural support. Thin metal bladders are expanded azimuthally between each coil and axially at the ends to pre-load the assembly. The sextupole assembly fits inside the solenoid bobbin, which provides support for the magnetic forces. The magnet exceeds design requirements with minimum training.

I. INTRODUCTION

Fig. 1 shows the arrangement of the ECR coil assembly which has two major components: The solenoid assembly with two solenoid coils spaced 50 cm. center-to-center and a smaller reversed coil between the large coils; this forms a "magnetic mirror" with field on axis shown in Fig. 2. The sextupole in the bore of the solenoids provides radial confinement for the plasma of the ECR source. Not shown is the external iron yoke that shields the surrounding space from the coil fringe fields. Design specification for the solenoids is 4 T and 3T for the field maxima on axis and 0.4 T at the central minimum. With the sextupole coils at design current of 385 A, the sextupole field on a 15-cm-diameter cylinder (the plasma vacuum wall) is 2.0 T

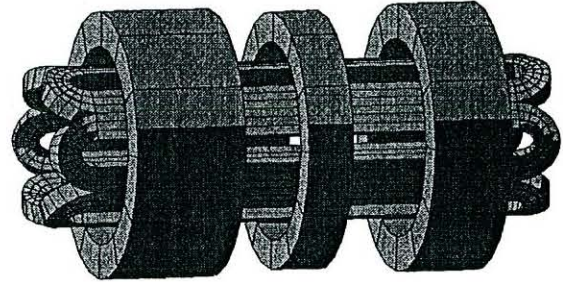Magnetic stored energy is 715 kJ with all coils at the design current given in Table I.

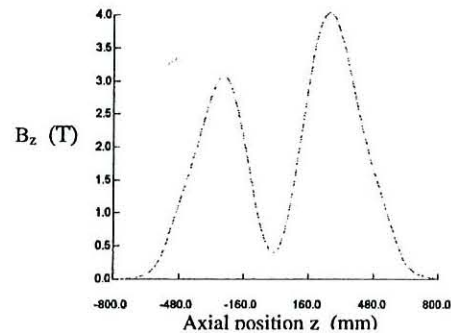Fig. 1 Coil configuration (OPERA 3d model)

II. COIL PARAMETERS

Fig. 2   Field along the axis

TABLE I
COIL PARAMETERS

	Solenoid 1	Solenoid 2	Solenoid 3	Sextupole
axial position of center (cm)	+25	-25	0	+1.5
ID (cm)	34.00	34.00	34.00	20.00
OD (cm)	45.82	45.82	44.13	27.20
depth (cm)	5.91	5.91	5.06	3.60
width (cm)	19.44	13.60	8.00	
turns/layer	112	80	46	
number layers	56	56	48	
turns/coil	6272	4480	2208	637
design current (A)	227	224	-243	385
B_{max}(T) at coil (at design current)	6.22	5.43	4.22	7.30

TABLE II
SUPERCONDUCTOR PARAMETERS

	Solenoids	Sextupole
wire size bare	1.57 mm x 0.88 mm	1.80 mm x 0.90 mm
wire size insulated	1.65 mm x 0.96 mm	1.90 mm x 1.00 mm
Cu/SC ratio	4.00	3.00
mm^2	80	200
I_c (A) at B, 4.2 K		
B=5 T	720-790	1080
B=6 T		860
B=7 T		640

III. SOLENOID CONSTRUCTION

The solenoid bobbin is a one piece Aluminum alloy forging machined to accommodate the three coils as shown in Fig. 3. All have a winding inner diameter of 34 cm. Table I gives the coil dimensions and winding parameters and Table II gives the parameters of the NbTi-Copper superconductor. All coils are "wet wound" using filled epoxy.[3] 0.05-mm fiberglass cloth is inserted between layers. Aluminum wire strip is wound on the outer diameter of solenoids 1 and 2 to provide a 10-mm band that limits radial deformation when energized. After winding, the inner diameter of the solenoid bobbin is machined to a uniform diameter to accommodate insertion of the sextupole assembly.
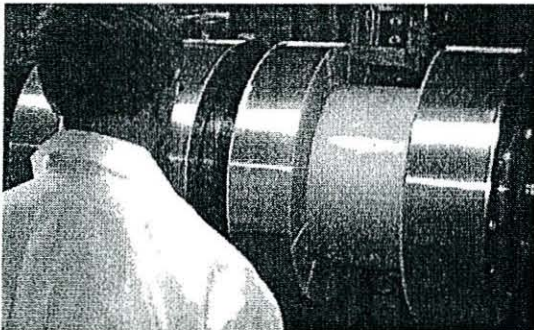

Fig. 3 Winding of the solenoid coils

III. SEXTUPOLE COIL CONSTRUCTION

Each "racetrack shaped" coil is wound in layers around a 20-degree, 81.9-cm. long, metal pole. The 20-cm. diameter inner and 27.2 cm. diameter outer surfaces are cylindrical. The cross-section of each side of the coil and that of the pole occupy 20-degrees in azimuth; each coil occupies 60 degrees of azimuth.

Thermal contraction of a sample winding was measured[4] earlier, and the results are summarized in Table III.

TABLE III
THERMAL CONTRACTION BETWEEN ROOM TEMPERATURE AND 77 K

Direction	Measured
Tangential (along conductor)	0.283
Axial (turn to turn direction)	0.383
Radial (layer to layer direction)	0.447

The central 34 cm. of the pole is made of iron to increase the sextupole field in the center, and the ends are aluminum. With these proportions, total axial thermal contraction of the pole matches that of the coil. Figs. 4a, 4b, and 4c show details of the coil construction.
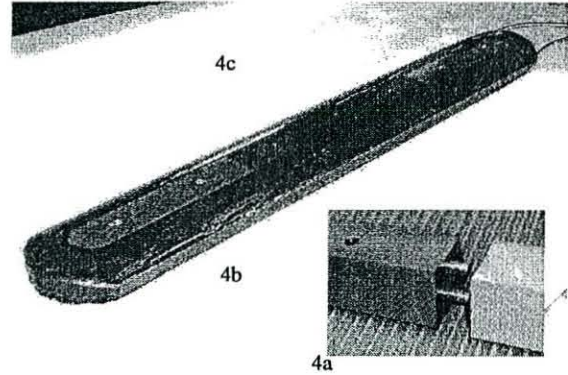

Fig. 4. 4a shows the Aluminum-Iron joint in the pole, 4b shows a coil before the ends are finished; 4c shows an end "shoe" of fiberglass-epoxy laminate fitted to the return end.

The coils are "wet wound" using filled epoxy[3] with 0.05-mm fiberglass cloth between layers. Winding must proceed in stages because of the limited pot life of the epoxy. Fig.5 shows the tooling that is required to closely control the dimensions of the coil.

Fig.5 Sextupole Tooling

IV. ASSEMBLY OF THE SEXTUPOLE COILS

The six sextupole coils are placed around the 20 cm OD stainless steel bore tube with an expandable bladder inserted between each coil to provide azimuthal compression. A wrap of 0.35-mm x 3-mm aluminum tape with 50% coverage is added to hold the six coils tightly against the bore tube. Two additional bladders are inserted between the return end of the coils and the adjacent steel flange that is welded to the bore tube. Fig. 6 shows the sextupole assembly before installation of the outer support tube and inflation of the bladders.
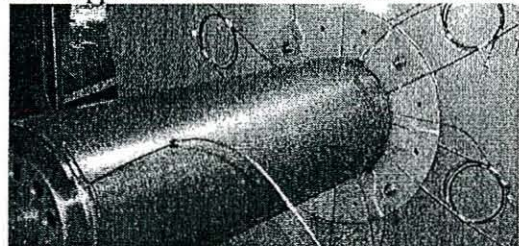

Fig. 6 Sextupole assembly before installation of the outer support tube and inflation of the bladders.

A. Expandable Bladders

The bladders consist of two flat sheets of 0.25-mm stainless steel stacked together and welded on the edges. A 3-mm OD stainless steel tube is welded to one edge through which fluid can pressurize the space between the two sheets. Thus the 0.5 mm-thick bladder is an "expandable shim" that can expand to compress the coils azimuthally and axially after a structural cylinder is placed over the assembled coils. Tubes attached to the azimuthal bladders can be seen in Fig. 6 on the right end adjacent to the large stainless steel flange. One of the two tubes connected to the end bladders is visible on the left adjacent to the small flange; these tubes will be bent to permit insertion of the aluminum support tube over the small end of the assembly. Fig. 7 shows an azimuthal bladder.
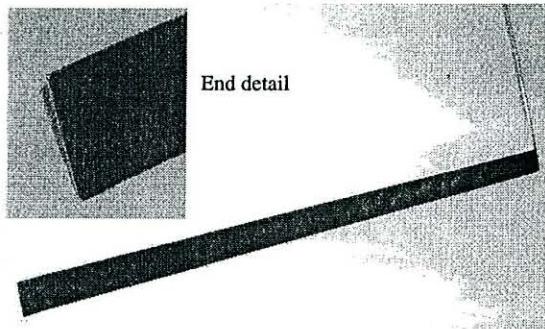

End detail

Fig. 7. One of the six 3.6 mm wide, 92 mm long, 0.5 mm thick inflatable stainless steel bladders

With the support tube in place, the assembly is heated to 65C. The azimuthal bladders are inflated to 10.4 MPa and the end bladders to 2.6 MPa with a liquid metal having a melting temperature of 47.2 C; the alloy, Incalloy[5] 117, has a very small volume change during solidification. By this means, the coils are uniformly compressed azimuthally and radially against the outer support tube, and axially between the flanges welded to the bore tube.

2. Epoxy Impregnation

After cooling, the assembly is vacuum impregnated with epoxy to fill the small gap left between the coils and the inner bore tube because of outward the expansion caused by azimuthal bladder inflation. Additional radial and azimuthal compression will be added because of the difference in thermal contraction of aluminum and coils during cooling to liquid helium temperature.

3. Support of the Sextupole by the Solenoid Bobbin

The interaction of the sextupole with the strong axial and radial field of the solenoids produces large forces; however, the 10 mm thick support tube is not stiff enough to prevent excessive deformation of the sextupole assembly under magnetic load. Therefore, the solenoid bobbin is used to limit deformation of the sextupole. The outer diameter of the sextupole support tube is machined to closely fit the inner bore of the solenoid bobbin. Fig. 8 shows the finished sextupole assembly being inserted into the solenoid assembly; there is approximately 65-μm radial clearance.
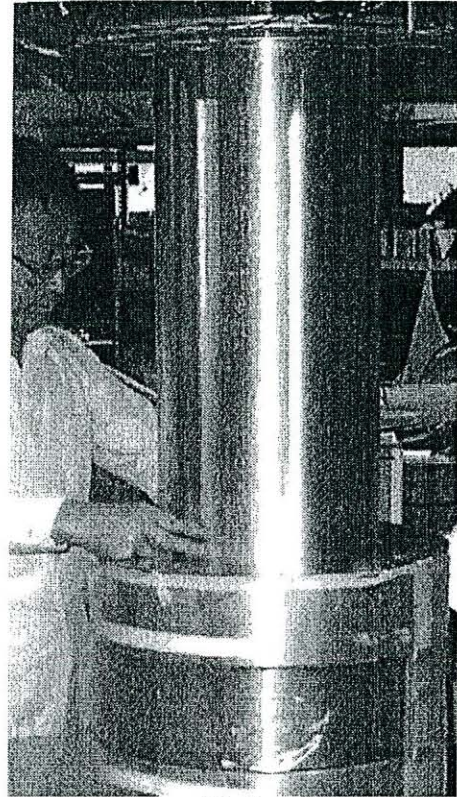

Fig. 8. Insertion of the Sextupole Assembly into the Bore of the Solenoid Bobbin

V. QUENCH PROTECTION

Each solenoid coil and each of the six sextupole windings is shunted by "back-to-back" diodes in series with a resistor to limit terminal voltage during quench. The diodes and resistors are at liquid helium temperature.

VI. TEST RESULTS

The magnet assembly, shown in Fig. 9, was tested in a 51-cm ID cryostat. Two tests were performed.

1. Solenoid Tests

First the solenoids were tested without the sextupole in a variety of field combinations to simulate the maximum fields at the coils and the axial forces that will be experienced in service. These forces include the inter-coil forces and the attraction between a solenoid and the iron shield that will be surrounding the cryostat. Table 4 gives the test currents. No quenches were experienced during these tests.
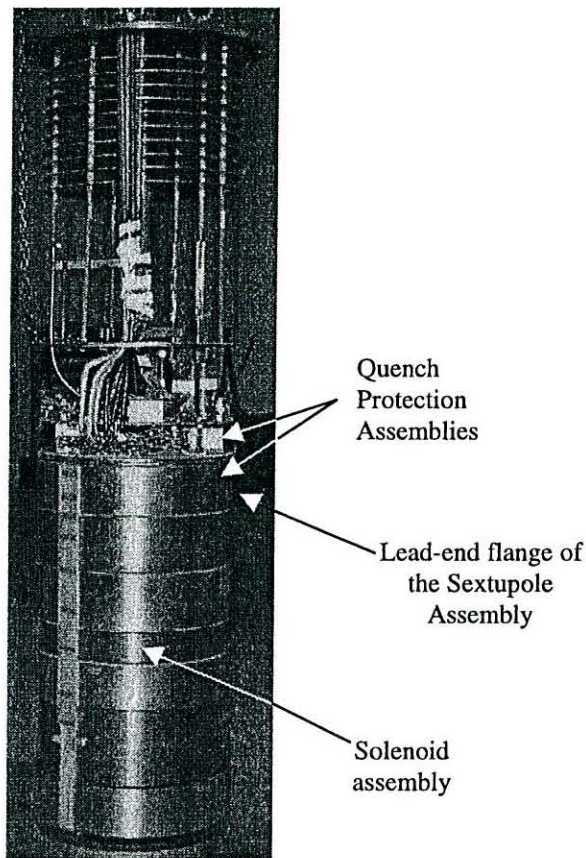
Fig. 9. Magnet assembly prepared to be tested in the 51 cm ID Cryostat

TABLE 4

SOLENOID TESTS

Coils operated individually

	coil	1	2	3
I (A)		270	300	-325
B_{max} (T) at above current		7.06	6.89	4.41
I_{ss}^{6} (A) at 4.2K		302	336	-501

Coils operated in pairs

	coil	1	2	3
I (A)		250	0	-250
B_{max} (T)		6.305		3.95
axial force (kN)		485		-485

Coils operated in pairs

	coil	1	2	3
I (A)		0	250.0	-250.0
B_{max} (T)			5.50	3.70
axial force (kN)			-326	326

A. Sextupole Tests

The second test included the sextupole coils. The sextupole experienced training quenches when tested by itself, and when tested in the progressively stronger solenoid

field. Fig. 10 shows the training behavior. Each quench originated in a sextupole coil, moving among the six coils as training proceeded; the solenoids quenched later due to heating from the sextupole coils. After 13 quenches, it reached 505 A with the solenoid currents at the design value; then the test was terminated. The design current of the sextupole with solenoids on at 100 % is 385 A; the "short sample" current under these conditions is 550 A. The magnet has not yet been thermally cycled to room temperature and re-tested.
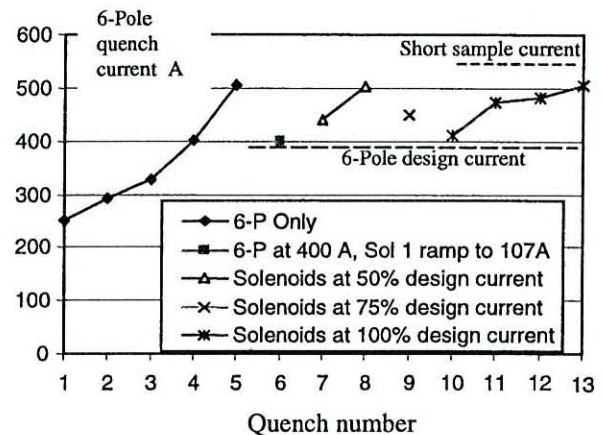

Fig. 10   Quench current of the sextupole v.s. quench number

The ECR cryostat is now under design and will incorporate cryocooler refrigeration and high T_c current leads.

VII. CONCLUSIONS

The ECR Magnet System meets the design field requirements.

"Expandable shims" made of two thin sheets of metal permanently inflated with a low-melting-temperature alloy can be used to fit coils tightly, with uniform compressive loading, into a simple support structure.

VIII. ACKNOWLEDGEMENTS

[1] C.M. Lyneis, Z.Q. Xie, C.E. Taylor: "Development of the third generation electron cyclotron resonance ion source", Rev.Sci.Instrum. **69**, 682 (1998)

[2] residual resistivity ratio = R (rm. temp.)/R(4.2 K)

[3] STYCAST 2850 FT BALCK and LV24

[4] Ken P.Chow and Gabrial A. Milos, "Measurement of Modulus of Elasticity and Thermal Contraction of Epoxy Impregnated Niobium-Tin and Niobium -Titanium Composites," Applied Superconductivity Conf., Palm Desert, Calif.,Sept. 13 - 18, 1998

[5] Indium Corporation of America

[6] I_{ss} is the "short sample" or critical current of the coil in its self field.